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Maturation of Dynamic Power Convertors for RPS Robotic Space Exploration

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NASA is developing dynamic power conversion technologies for future robotic space science and exploration missions powered by Radioisotope Power Systems (RPS). The Dynamic Radioisotope Power Systems (DRPS) Project is working to mature numerous dynamic power convertors and controllers for potential infusion into future flight generators. Maturation of power conversion technologies is being managed by the RPS Program and executed by the DRPS Project and Thermal Energy Conversion Branch located at NASA's Glenn Research Center (GRC). Convertor maturation includes multiple convertor technology development contracts to deliver new prototypes and continued testing of relevant legacy convertors, commissioned during past projects. The convertor technology development contracts include two Stirling contractor teams and one Brayton team. All contracts have now completed prototype fabrication and testing planned during Phase 2. Government assessment of the new prototypes includes verification of performance in relevant environments and validation of the design with a focus on robustness.

I. NEW PROTOTYPES

The current DRPS technology development effort builds on past lessons-learned and incorporates new requirements focused on demonstrating convertor robustness to critical environments. This effort is intended to gather data on candidate dynamic conversion technologies to fill knowledge gaps, assess the performance of prototypic units, and elicit generator requirements[1]. The design life and power requirements enable a long-life, 100-500 W_e generator at beginning of life and populated by multiple convertors operating at a derated power level to enable redundancy and high reliability. New requirements introduced in this development effort include an increased rejection temperature of 175 °C, a constant acceleration load of 5g in 3 orthogonal axes for an extended period, and the ability to survive a temporary loss of electrical load. These requirements ensure future DRPS meet performance, life, and reliability expectations while decreasing risk through implementation of robust designs.

The contracts included three phases that cover design, fabrication, and test support during government verification and validation (V&V) testing. Phase 2 has been completed by all contractors and prototypes have been delivered to GRC. Each Stirling contractor delivered two convertor prototypes while the Brayton contract delivered a single convertor prototype and a dedicated turbo machine for vibration testing.

All delivered prototypes will undergo government verification and validation (V&V) testing to ensure initial quality, verify contractor measurements, and validate requirements and robustness. The V&V convertor tests shown in Table I will be carried out through a combination of inspections, analysis, and tests to demonstrate a high Technology Readiness Level (TRL). There are four main areas: acceptance/performance verification, vibration testing, centrifuge testing, and robustness testing. Robustness testing is intended to complete any remaining thermal cycles that were not completed during production, with the desire of completing a total of 30. Track 4 also contains an optional test for loss of electrical load if that test was still incomplete for a convertor. In addition, the units will be reconfigured into a dual-opposed assembly and the residual disturbance force will be measured using load cells with the assembly on a rigid connection to ground.

TABLE I. Verification and Validation Effort.

Sequence	Focus	Objective 1	Objective 2
Track 1	Performance Testing	Acceptance and performance verification	Baseline data (steady state at single point)
Track 2	Vibration Testing	Qual level random vibration test	Optional inspection
Track 3	Centrifuge Testing	Constant acceleration test	Optional inspection
Track 4	Robustness Testing	Thermal cycling	Measure residual jitter from synchronized pair

I.A. SRSC Design and Performance Testing

The Sunpower Robust Stirling Convertor (SRSC) prototype design and generator concept were developed by Sunpower Inc. and Aerojet Rocketdyne.[2] The generator concept includes multiple dual-opposed convertor pairs arranged around a central stack of GPHS Step-2 fuel modules, where one pair is redundant. A convertor pair would be disabled in the case of a single convertor failure and the amplitude of the remaining convertors would be increased to maintain generator design power output. The fuel stack design and assembly would utilize existing designs and methods and the convertor heat rejection

flange would bolt to the generator housing, making subassembly verification and integration straight forward. The SRSC generator concept did not employ a sealed inert gas, potentially putting any graphite materials at risk of attack in a Martian atmosphere.

The SRSC includes changes that improve robustness and ease startup, compared to the Advanced Stirling Convertor (ASC). While the ASC and SRSC both use gas bearings to maintain non-contacting running clearances needed for wear-free operation, changes were made to increase the SRSC bearing stiffness for improved robustness during lateral loading. Additionally, the gas bearing system now employs more gas pads, a check valve filter, and a redundant check valve. A passive collision prevent system has also been implemented to meet the loss of load requirement, where the electrical load is removed for 10 seconds before being restored. The passive collision prevent system works by dissipating thermodynamic cycle energy for a portion of the cycle when the moving components exceed a threshold amplitude. This patented Loss of Load Tolerance (LLT) function could prevent damage during ground test errors or piston excursions caused by the random vibration environment. Sunpower has incorporated the loss of load test into production processes to enable LLT verification on all units. As a backup to the LLT, the design also includes bumpers that could be removed.

Sunpower delivered SRSC Pair 1 to GRC in October 2020. SRSC Pair 1 employed bolted joints to enable disassembly and inspection. Figure 1 shows the larger bolted flange design (7.2 kg mass) and an overlay of the smaller hermetic design (3.4 kg mass) used in the Pair 2 prototypes, which are currently being fabricated as part of Phase 3. SRSC Pair 2 changes include hermetic enclosure, improved running clearance geometry, implementation of robust position sensors, and material replacement for a bumper and an O-ring, to mitigate a compatibility risk.

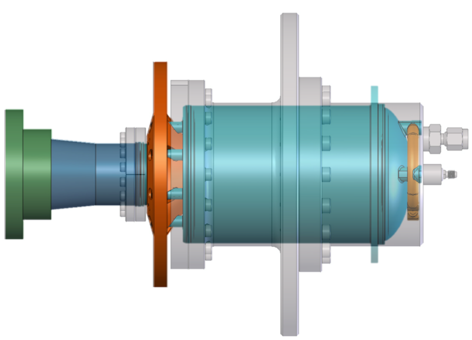

Fig. 1. SRSC hermetic prototype design overlaid on the bolted flange prototype design.

SRSC Pair 1 were originally designed to produce 64 W_{AC} of electrical power output while at 700 °C on the hot end and 100 °C on the cold end, with a target conversion efficiency of at least 24%. The delivered prototypes underperformed due to lack of optimization of a new internal component and due to non-optimal running clearances. During initial vendor testing of unit 1, random fiber regenerator debris was observed inside the engine. The proposed resolution was a wrapped screen regenerator fabricated from high-temperature woven screen material. This approach greatly improved robustness, however the resulting pressure drop hurt performance and conversion efficiency. Additionally, the clearance seals were less than optimal due to errors in implementation of an alignment tool. The compromised moving components and resulting flow losses led to a conversion efficiency of roughly 22%. To improve performance without sacrificing robustness of Pair 2, currently in production, the error was corrected with the alignment tool and a new measurement process was implemented to measure running clearances prior to first operation. In addition to a robust regenerator, other important accomplishments include demonstrating the passive collision prevention system on both Pair 1 convertors and operating at the maximum rejection temperature of 175 °C for approximately 10 hours on each convertor prior to delivery.

SRSC Pair 1 has completed V&V Track 1, where SRSC #1 achieved 47.3 We at 21.7% efficiency while SRSC #2 achieved 50 We at 23.2% efficiency for the nominal test point. During performance testing in Track 1, a relatively high leak rate was observed through the elastomeric O-rings. The O-ring glands had also been designed to use metal seals. To improve the leak rate, the units were returned to Sunpower and metal seals were installed and leak tested. The leak rate was not improved due to imperfect geometry of the gland surfaces that could not be rectified at that stage of assembly. Thus, new elastomeric O-rings were installed and the units were returned to GRC. The performance of SRSC #2 was unaffected by the attempted improvement, however SRSC #1 had experienced a 3-watt power loss once it was returned to test at GRC. SRSC #1 performance was remeasured to be 43.4 We at 20.2% efficiency. It was found that when the prototype bolted flange design is at the low charge pressure employed during shipment, the heater head is at an elevated risk of lateral movement due to the lack of a piloting feature and low bolted flange preload margin. Movement of the heater head is believed to have increased fluid flow and heat transfer losses inside the convertor, resulting in lost available work and a lower indicated power. Once the issue was understood, protocols were put in place to mitigate the risk. The risk is limited to Pair 1 because the hermetic design used in Pair 2 has piloting features and welded joints that prevent the lateral movement.

Figure 2 shows the data for SRSC Pair 1. Performance testing was carried out during the first few hundred hours of operation, after which baseline data was collected to serve as a comparison after environmental tests are

completed. SRSC #1 experienced more performance testing than SRSC #2 while diagnosing the power loss observed on that unit. The power output has been otherwise remained steady during performance testing and during the 2,800 hours of extended operation. For SRSC #2, initial testing appeared steady, however a small decreasing trend in power output started to emerge during the nearly 4,200 hours of extended operation, reaching 1.8% before the unit was shut down for investigation. Several areas of that setup were inspected, including the alternator output, rack control, and the working gas concentration. Using RGA measurements, nitrogen was observed in the charge gas at a level estimated to be around 2% of the total volume. The power output recovered to within 99.7% after replenishing the charge gas with high purity helium. This level of air ingress has not been observed on other prototypes and appears to be isolated to that convertor's gas management system, which is currently under investigation to identify a root cause.

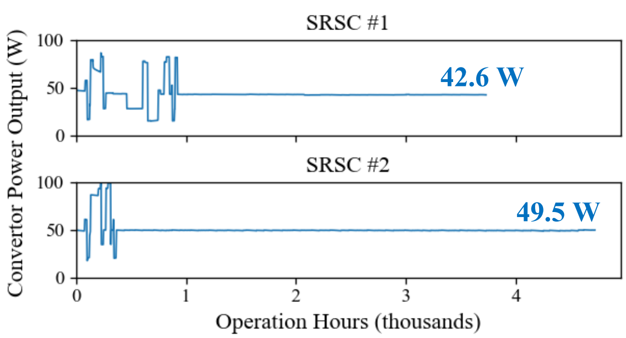

Fig. 2. SRSC #1 and #2 Performance Testing and Baseline Performance Data.

SRSC #1 and #2 are mounted individually during Track 1 and support testing for Track 2 and 3. During Track 4, they will be joined in a dual-opposed configuration. Figure 3 shows SRSC #1 in the Stirling Research Lab at Glenn Research Center.

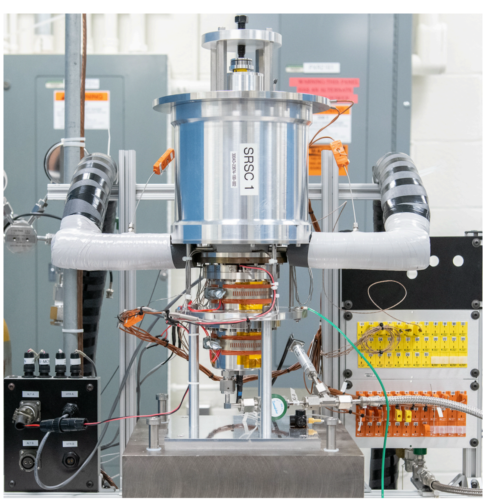

Fig. 3. SRSC #1 performance testing at NASA GRC.

I.B. FISC Design and Performance Testing

The Flexure Isotope Stirling Convertor (FISC) prototype design and generator concept were developed by American Superconductor (AMSC) and Teledyne Energy Systems, Inc. (TESI). Similar to the SRSC generator concept, multiple dual-opposed convertor pairs are arranged around a central stack of GPHS Step-2 fuel modules, where one pair was redundant, and the fuel stack design and assembly would utilize existing designs and methods. One major difference from the SRSC generator concept is in how the convertors are integrated into the generator housing. Convertor subassembly verification would be completed prior to partial disassembly, where the heater heads and alternators would be separated from the central coupler and integrated into the housing as separate components. This approach would require numerous hermetic joints on the housing for each heater head and alternator subassembly and machining of hundreds of rejector gas passages needed on the cold side of the convertor. The FISC generator concept contains a sealed internal gas volume and would be filled with xenon or argon to protect hot components from oxidation.

The FISC includes changes that improve performance, reduce mass, and ease manufacturability, compared to the Technology Demonstration Units (TDC). While the TDC and FISC designs use flexure bearings to maintain non-contacting running clearances needed for wear-free operation, some aspects were changed to improve upon the TDC design. The FISC employs a moving-magnet alternator instead of the previous moving-iron design and the engine contains new alignment features that help streamline assembly. The prototype design is non-hermetic to permit disassembly and inspection during the government assessments but contains provisions to enable hermetic laser welds during flight production. To meet the temporary loss of electrical load requirement, the FISC contains organic material bumpers that are designed to absorb energy during collisions between the moving components and stationary gas manifold without permanent degradation or compromising life or reliability. Analysis completed at GRC, under project risk mitigation, suggests the bumper material would yield during collisions so the loss of electrical load test is not planned on FISC Pair 1.

AMSC delivered FISC Pair 1 to GRC in August 2021. The FISC prototype design employs bolted joints to enable disassembly and inspection. Figure 4 shows the bolted joint prototype design (4.1 kg mass), which contains laser weld provisions for hermetic sealing that are intended to be used along with the bolted joints in the flight design. The FISC prototypes were originally designed to produce 70 W_{AC} electrical power output while at 650 °C on the hot end and 100 °C on the cold end, with a target conversion efficiency of at least 24%. Performance of FISC #2 was measured

during acceptance and performance verification testing and found to exceed the performance requirement, achieving 57.5 W_e at 25.1% efficiency. The FISC prototypes did not meet the maximum rejection temperature requirement of 175 °C due to a non-flight material located in the alternator. Thus, the maximum rejection temperature was limited to 150 °C for V&V testing. Also, the prototypes were about 20% under the 20 W_e/kg specific power requirement.

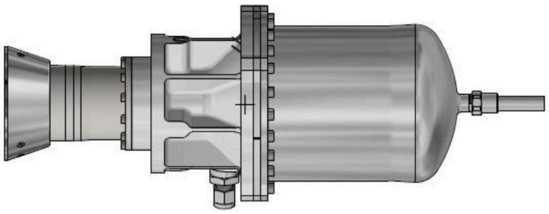

Fig. 4. FISC bolted joint (and hermetic) prototype design.

FISC #1 testing has been delayed due to misalignment of the position sensor core. The position sensor was required for prototype characterization and is a non-flight feature. To repair the misaligned core, a precision bending tool was fabricated and the repair process was completed using a CMM to verify success. With the repair now successfully completed on FISC #1, V&V testing will begin. Figure 5 shows FISC #2 in the Stirling Research Lab at Glenn Research Center. No additional units have been ordered from AMSC at this point.

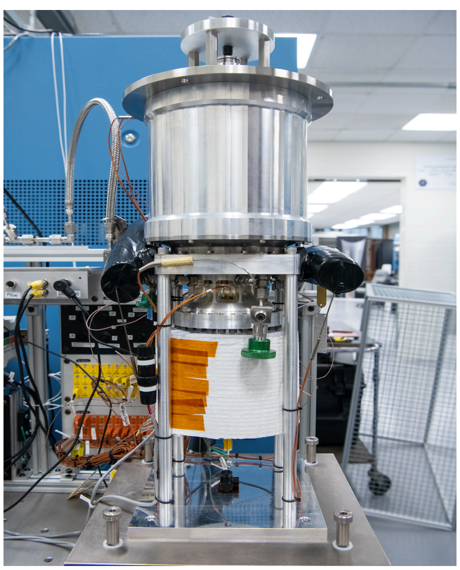

Fig. 5. FISC #2 performance testing at NASA GRC.

Track 2 testing includes 24-hour performance test after installation in the vibration test fixture. There is another 24-hour performance test after the vibration test to ensure no immediate damage occurred. The convertor will then be installed in the extended operation insulation package and tested for 750 hours. An optional inspection is followed by another 250-hour test if the inspection is pursued. The vibration test fixture will utilize a radiant heat source to best simulate the thermal and mechanical interfaces found in the generator concepts. The SRSC and FISC generator concepts employed radiant coupling from the central stack of GPHS modules to the hot side of each convertor.

Figure 6 shows the data for FISC #2. Performance testing was carried out during the first couple hundred hours of operation, after which baseline data was collected to serve as a comparison after environmental tests are completed. The performance for FISC #2 has been very steady and the unit is ready for random vibration testing.

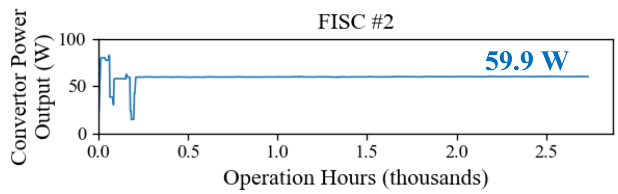

Fig. 6. FISC #2 Performance Testing and Baseline Performance Data.

I.C. Random Vibration Testing

Track 2 of the V&V Plan includes random vibration testing. To simulate radiant heating, a radiant heat source was constructed from Kanthal-D, a high-temperature material able to tolerate the more than a 1,000 °C element temperature needed to enable the convertor hot-end temperatures during vibration testing. Different from past vibration tests, the heater heads of both SRSC and FISC generator concepts are unconstrained at the hot end, while the rejection flange and alternator are rigidly connected to the fixture. Figure 7 shows the SRSC prototype installed in the fixture used to conduct random vibration and constant acceleration testing. The fixture will also accommodate the FISC prototype.

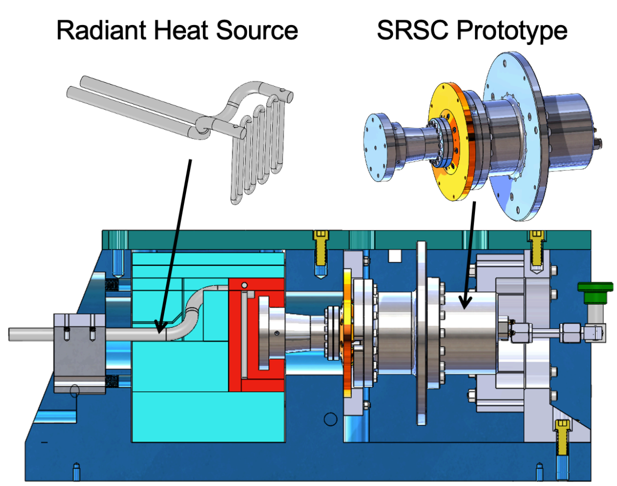

Fig. 7. SRSC prototype installed in fixture used to carry out environmental testing.

The vibration acceleration spectral density (ASD) level, shown in Figure 8, was derived using the DRPS Environmental Requirements Document, which is largely based on requirements found in GSFC-STD-7000B (GEVS) and NASA-HDBK-7004. The qualification profile found in the environmental requirements document was reduced using the worst-case assumption of a 50 kg generator mass. The result is a qualification Grms value of 9.52 dB and flight acceptance Grms value of 6.73 dB. These values are lower than the design requirement employed during Phase 1 of the prototype contracts, which had a Grms value of 10.35 dB.

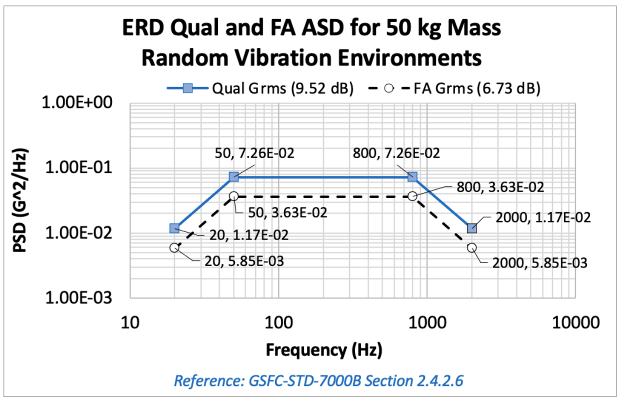

Fig. 8. V&V Qualification and Flight Acceptance ASD.

I.D. Turbo-Brayton Convertor (TBC)

The Turbo-Brayton Convertor (TBC) prototype design and generator concept were developed by Creare Inc. and Aerojet Rocketdyne.[3] The TBC generator concept contains two convertors to provide 100% redundancy and enable counter-rotating turbo-alternators while both convertors operate at half power. While both convertors share the heat source assembly, each convertor contains its own turbomachine, recuperator, and radiator with a high surface area. Similar to the other generator concepts, Whipple shielding could be used to mitigate the risk of damage due to the micrometeoroid environment. The heat source assembly uses six GPHS Step-2 modules inside an evacuated multi-layer insulation to maximize insulation efficiency and protect the GPHS modules from oxidizing environments. Two separate gas flow channels are located in the heat source assembly to enable heat input to each convertor. The generator concept was designed to ensure it fits inside the DOE shipping container, although it used most of the margin inside the container due to the size of the radiator.

The TBC prototype design's point of departure is a flight cryocooler that successfully operated on Hubble's Near Infrared Camera and Multi-Object Spectrometer (NICMOS) instrument. It includes changes necessary for power production as well as changes that improve bearing performance and increase temperature tolerance to accommodate DRPS requirements. The TBC prototype uses hydrodynamic journal bearings and thrust bearings to maintain non-contacting running clearances needed for wear-free operation. The turbo machine consists of a single rotating shaft with turbine and compressor impellers located at each end. The shaft contains a rare-earth magnet which rotates inside a stationary coil and iron of the rotary alternator. The TBC prototype was designed to produce 337 W_{AC} of electrical power output while at 730 °C on the hot end and 100 °C on the cold end, with a minimum conversion efficiency of 24%. The prototype was intended to operate across the specified power levels and temperatures, including half heat input and the high rejection temperature of 175 °C. The test plans changed based on pervasive compressor surge, an aerodynamic instability mode where the fluid velocity component varies periodically and may even become negative for deep surge conditions. Figure 9 shows the TBC prototype without any insulation installed.

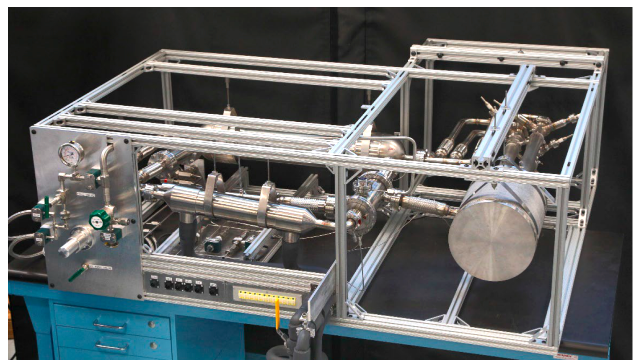

Fig. 9. Turbo Brayton Convertor (TBC) Prototype Assembly, *insulation not shown*.

During performance testing, the prototype reached the design point temperatures of 730 °C at the turbine inlet and 100 °C at the compressor inlet. Compressor surge limited the maximum design speed to 130,000 rpm compared to the design value of 161,000 rpm. The maximum alternator power at this condition was measured to be 135 W, resulting in a converter efficiency of 14.4%. The half-power condition could be reached as it only required an operating speed of 124,000 rpm at the same turbine and compressor inlet temperatures. At the half-power condition, the convertor produced 110 W at 13.2% efficiency versus a predicted 159 W and 22.6% efficiency. As testing continued, worsening leaks in the test setup caused a gradual pressure loss which lowered the surge threshold and further reduced the maximum operating speed.

After this testing, a new compressor diffuser was manufactured to improve the surge threshold and the leaks were repaired. The test setup was reassembled and checked out in 100% helium. Previously, compressor surge

occurred at 100,000 rpm in helium, but 120,000 rpm was reached without compressor surge with the new diffuser. With that improved position, testing was continued in an attempt to reach full power. During bakeout prior to charging with the final working gas, axial contact occurred between the compressor diffuser and the compressor impeller, causing the turbo machine to seize. Inspection revealed damage that would require the refurbishment of several components. The decision was made to defer those repairs to a later effort and end the contract.

To meet the temporary loss of electrical load requirement, the TBC prototype design was able to sustain stable operation during loss of electrical load without compromising life or reliability. This capability was successfully tested, albeit unintentionally, when the electrical load was lost during a performance test. The rotor speed increased abruptly from 120,000 rpm to 190,000 rpm and the emergency load did not engage because the actual alternator voltage turned out to be less than predicted and under the trip threshold. The cycle thermodynamic energy was dissipated through drag losses without reaching the resonant bending frequency of the shaft, safeguarding the convertor from damage during the 5-minute event.

RPS run continuously after fueling and, therefore, must operate through the launch environment. Creare Brayton cryocoolers have completed vibration qualification tests and spaceflight launches, however, none of those systems were required to operate during launch. To mitigate the project risk of catastrophic damage during the launch environment due to contact of moving and stationary components inside the turbo machine, a dedicated turbo machine was designed and constructed for vibration testing. Figure 10 shows the dedicated turbo machine on the vibration table at National Technical Systems (NTS) in Boxborough, MA.

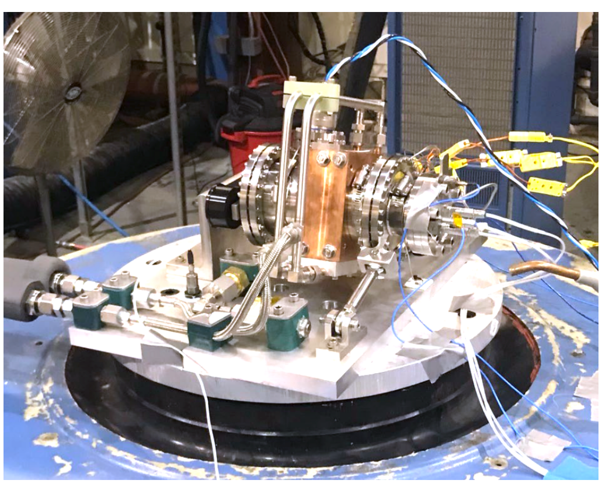

Fig. 10. Dedicated turbo machine for vibration testing.

During the vibration test, the unit contained a working gas pressure of 360 kPa and mixture of 85% xenon/15% helium. It utilized a rotor speed of 140,000 rpm and the housing temperature was held between 40-60 °C. Dynamic CFD analyses indicated acceptable bearing performance and the vibration test successfully validated that model and demonstrated robust operation of the prototypic bearing design. This was the first test of its kind and no damage or degradation occurred, demonstrating robustness in the TBC prototype design. There was a single test anomaly that is being studied but doesn't affect the findings of the test.

II. LEGACY CONVERTORS

Legacy convertors were commissioned during past development efforts to provide performance verification and life and reliability data from high fidelity demonstration units and engineering units. Legacy units utilized temperature resistant materials and non-contacting bearings to demonstrate wear-free, long-life operation and were validated against performance specifications before undergoing extended operation testing. A total of eight Stirling convertors remain on test at GRC in extended operation. Legacy convertors include both gas-bearing and flexure-bearing designs. Many of the units are used to support ongoing controller or generator concept development or to continue extended operation to generate reliability data. Some units have been taken offline due to failure and investigated to identify improvements for future designs. Other units remain in storage, either because they are older deigns and less relevant or designated for tactical testing. Table II shows the recently updated extended operation hours for Legacy convertors and new prototypes.

Table II. Summary of on-going Stirling convertor tests.

Test Article	Hours	Years	Cycles (B)	Vibe	Spin	Note
TDC #13	133,555	15.2	39.2			World Record
TDC #15	131,969	15.1	38.8			
TDC #16	131,969	15.1	38.8			
TDC #14	105,616	12.1	31.0			Disassembled
ASC-0 #3	103,273	11.8	38.7	FA		
ASC-L	64,769	7.4	23.8	FA		EM controller
ASC-E3 #4	51,883	5.9	19.1	FA		Eng. Unit
ASC-E3 #9	37,926	4.3	14.0			Eng. Unit
SES #2	26,348	3.0	7.8	FA	5g axial 20 radial	Eng. Unit
SRSC #2	4,837	0.6	1.7			Bolted joints
SRSC #1	3,728	0.4	1.3			Bolted joints
FISC #2	2,736	0.3	0.8			Bolted joints
FISC #1	0	0.0	0.0			Bolted joints

Extended Operation Data as of 2/7/22 *FA: Flight Acceptance*

The Technology Demonstration Convertor (TDC) is a flexure-bearing design developed during the 110W Stirling Radioisotope Generator (SRG-110) flight development project. A total of sixteen TDC prototypes and two engineering units were produced during the flight contract between 2000-2006. TDC #13 is currently the longest

running heat engine in the world with over 15.2 years of error-free operation. It was paired with TDC #14 until the DRPS project elected to disassemble and inspect the unit after 12 years of error-free operation. There were no unanticipated observations made during the assessment, successfully demonstrating a long-life design. There was some expectation to find evidence of oxidation because both units had experienced ingress of air through the elastomeric O-rings during roughly the first 5,000 hours of life. The units were later hermetically sealed but not before detecting nitrogen, an indication that the oxygen had been consumed. During the inspection, oxides were observed on some surfaces, matching those found in the hottest regions of the stainless-steel random fiber regenerator. Figure 11 shows the longest running flexure-bearing and gas-bearing free-piston Stirling convertors currently operating at NASA, where the longest running flexure-bearing convertor holds the world record for longest running Stirling engine.

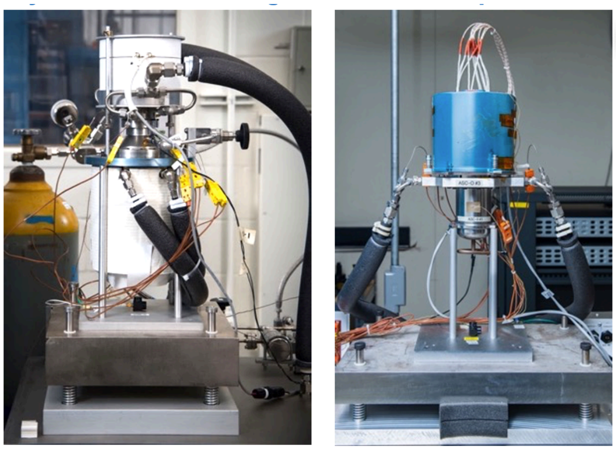

Fig. 11. Longest running flexure-bearing Stirling convertor (TDC #13 @15.2 years) and longest running gas-bearing Stirling convertor (ASC-0 #3 @11.8 years).

Before inspection of TDC #14, an effort was made to adjust the operating conditions as closely as possible to early operation for a direct performance comparison. Once the earlier operating point was reestablished, the resulting performance of TDC #13 & #14 both matched early performance data within the measurement uncertainty, demonstrating the long-life design and no degradation had occurred. Figure 12 shows power output data for the TDC under extended operation in the Stirling Research Lab at GRC. The various changes in power output for each convertor were explained thoroughly in Ref #4 and all have been correlated to a change in facility or set point. The noticeable drop for TDC #15 & #16 around 105k hrs was due to half-power tactical testing. Also, SES #2 has less hours because it remained in storage for 10 years before undergoing random vibration, centrifuge testing, and continued extended operation.

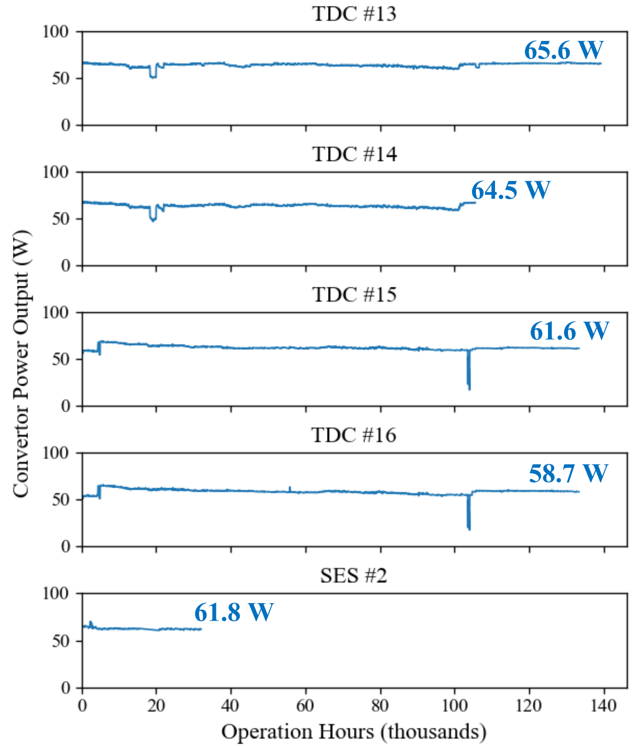

Fig. 12. Extended Operation Data from Technology Demonstration Convertors (TDC).

The ASC was developed for the Advanced Stirling Radioisotope Generator (ASRG) flight development project. A total of 17 ASC prototypes and 20 engineering units were produced between 2007-2015. Two flight units were in production when the ASRG contract was canceled and remain preserved in bonded storage at GRC. Based on available supporting facilities, four ASC continue to operate in extended operation and have accumulated over 23 years of operation. Other ASCs are used for tactical testing based on need. ASC-0 #3 is currently the longest running ASC with over 11.8 years of operation. ASC-L has accumulated over 7.4 years of operation while under control of the Single Convertor Controller (SCC), a fault-tolerant engineering model controller developed by the Applied Physics Laboratory.[5] Some early ASC units degraded due to imperfections caused by improper controls during production while other units were damaged due to overtest conditions experienced during controller ground testing. Disassembly and inspection helped identify needed design revisions that improved thermal stability of running clearances, robustness to overstroke conditions, and measures added to increase tolerance to small particle debris. Figure 13 shows power output data for the ASC under extended operation in the Stirling Research Lab. Delivery of the units shown was staggered in time. All changes in power output have been correlated to a change in facility or set point.

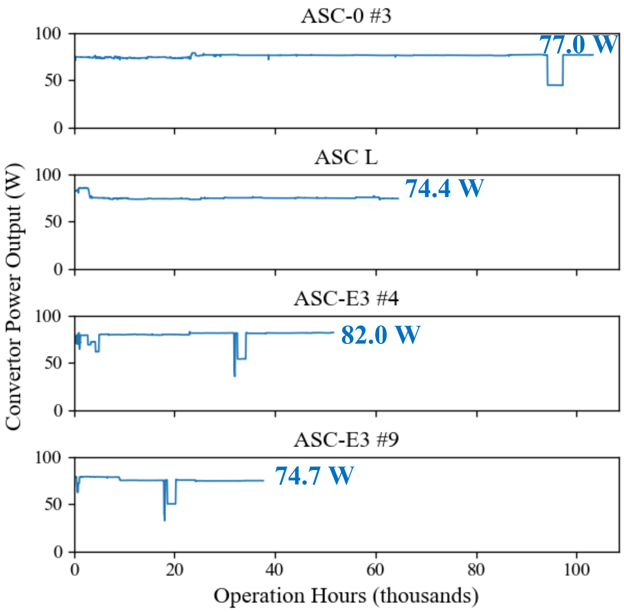

Fig. 13. Extended Operation Data from Advanced Stirling Convertors (ASC).

The key roles of testing at GRC are to provide government verification and validation of convertor performance to design specifications and to build a performance database to support life and reliability estimates. These roles have traditionally been fulfilled through 24/7 unattended operation of convertors and testing performed in relevant environments aimed to simulate the expected mission lifecycle a Stirling convertor would experience in a radioisotope power system. All testing performed at GRC uses electric heat sources to simulate the nuclear fuel in a fueled RPS.

Unattended 24/7 operation is enabled through dedicated test racks which provide software with user controls, data acquisition, automated fault detection and shutdown capability, and hard-wired protections in case the software functions fail. These systems are continuously being improved to provide better data and increased protection to the hardware and data retention. All parameters and calculations are averaged every 2-seconds to create a data point, which is stored in the local database. The database stores a buffer of 96 hours of 2-second data, which is automatically downloaded and saved daily to a remote, backed up data center. This data is also reviewed regularly through automated plotting routines that enable engineers to quickly assess the performance of the convertor and any factors contributing to a change in the performance. In addition, the dynamic signals sampled at a 7 kHz rate are also automatically saved to the data center and can be used to help investigate data further, as needed. An automated text functionality communicates ongoing changes in the test setup to the cognizant engineers responsible for the testing.

III. CONCLUSIONS

NASA's RPS Program and DRPS Project are maturing power conversion technologies for potential infusion into future flight generators. Convertor maturation efforts include completing multiple convertor technology development contracts, which have delivered 5 prototype convertors for evaluation and assessment. Of the delivered prototypes, four Stirling convertors are under test at GRC, while the Brayton prototype testing is being replanned due to technical setbacks. All contracts have completed Phase 2 and one contract is building additional convertors under Phase 3. Government verification and validation testing is underway by subjecting the prototypes to relevant environments to verify performance and robustness. Key environments include thermal conditions to simulate lunar and Mars environments, launch vibration to simulate rocket lift off, constant acceleration to simulate spin stabilization and entry decent and landing, and thermal cycling to simulate lunar diurnal cycles. So far, the Stirling convertor technologies that have been received show a lot of promise for passing critical environmental tests, which would elevate the technology readiness level for future application.

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